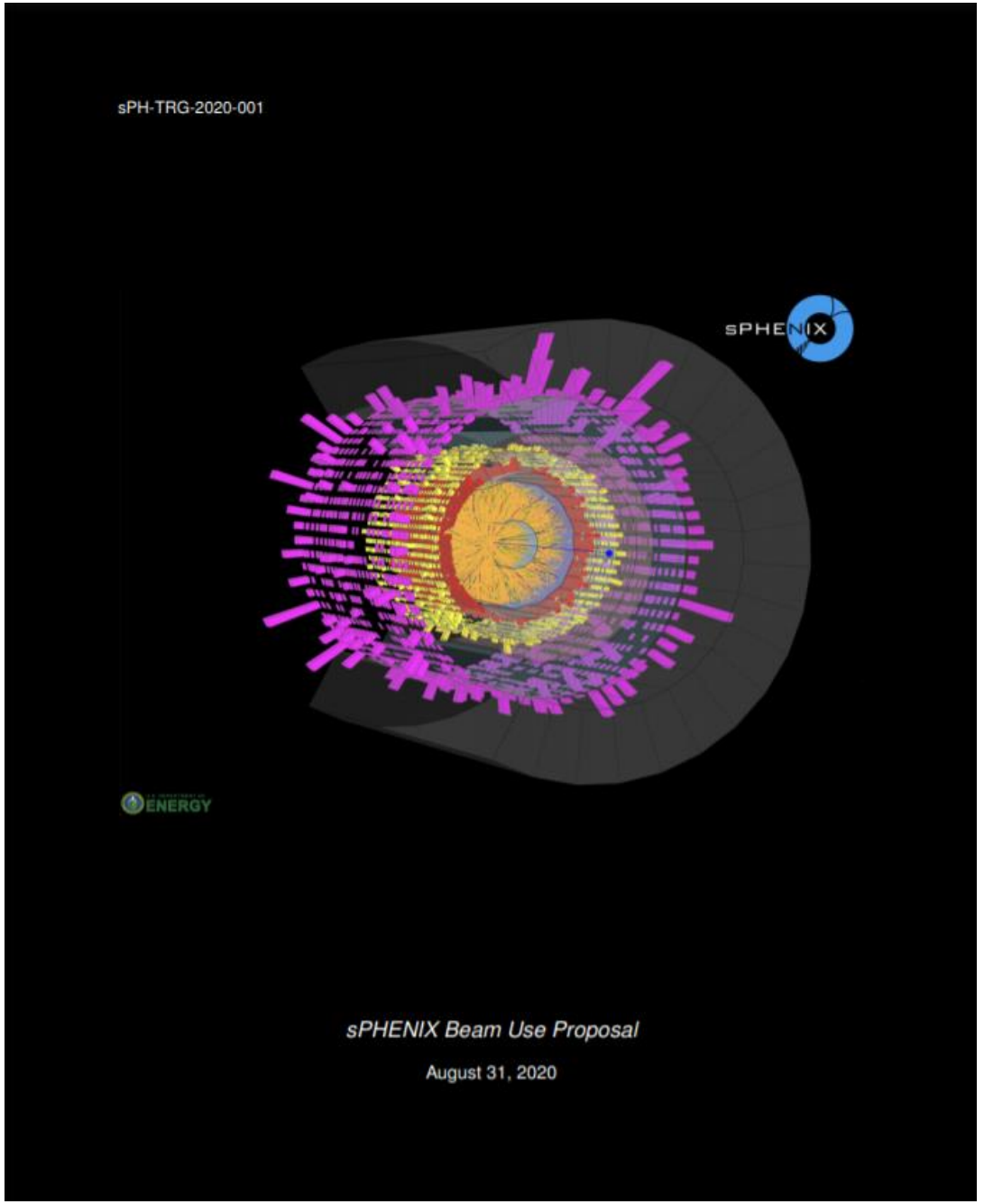
The future Cold QCD program with the sPHENIX detector

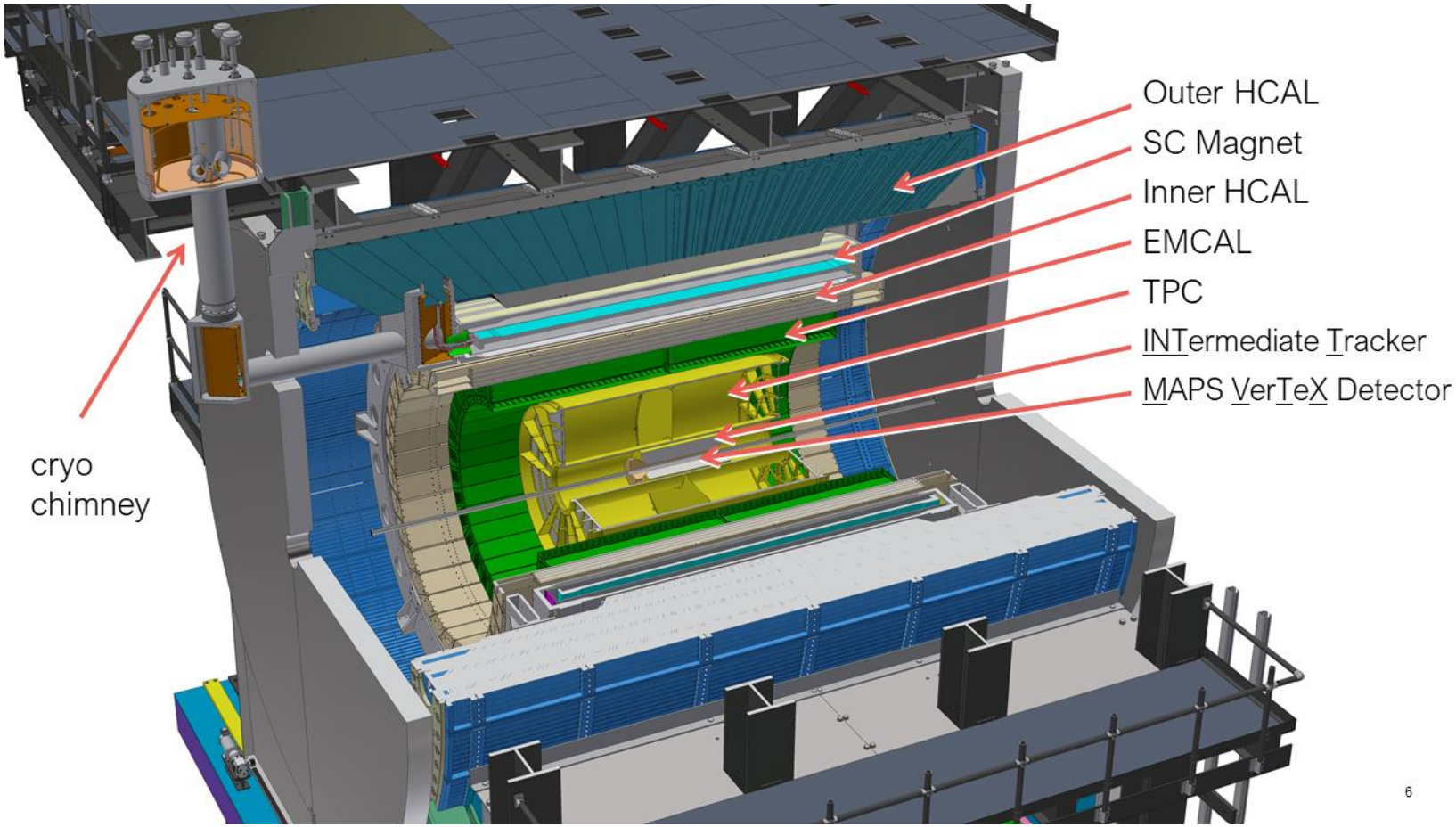
Desmond Shangase (University of Michigan) on behalf of the sPHENIX Collaboration

RHIC/AGS Annual Users Meeting - October 22nd 2020

Contents

- sPHENIX Detector Design + Run
- Cold QCD Measurements
  - Transverse Spin Measurements
  - Unpolarized Measurements





sPHENIX Detector

- Full azimuthal detector (Central Barrel)
- Data collection expected to begin 2023
- Cold QCD Physics Program
  - Parton Dynamics (TMD PDFs)
  - Proton/Nuclear Structure (PDFs)
  - Hadronization + Jet Substructure (FFs, $\hat{q}$, etc.)

sPHENIX Detector

sPH-TRG-2020-001

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

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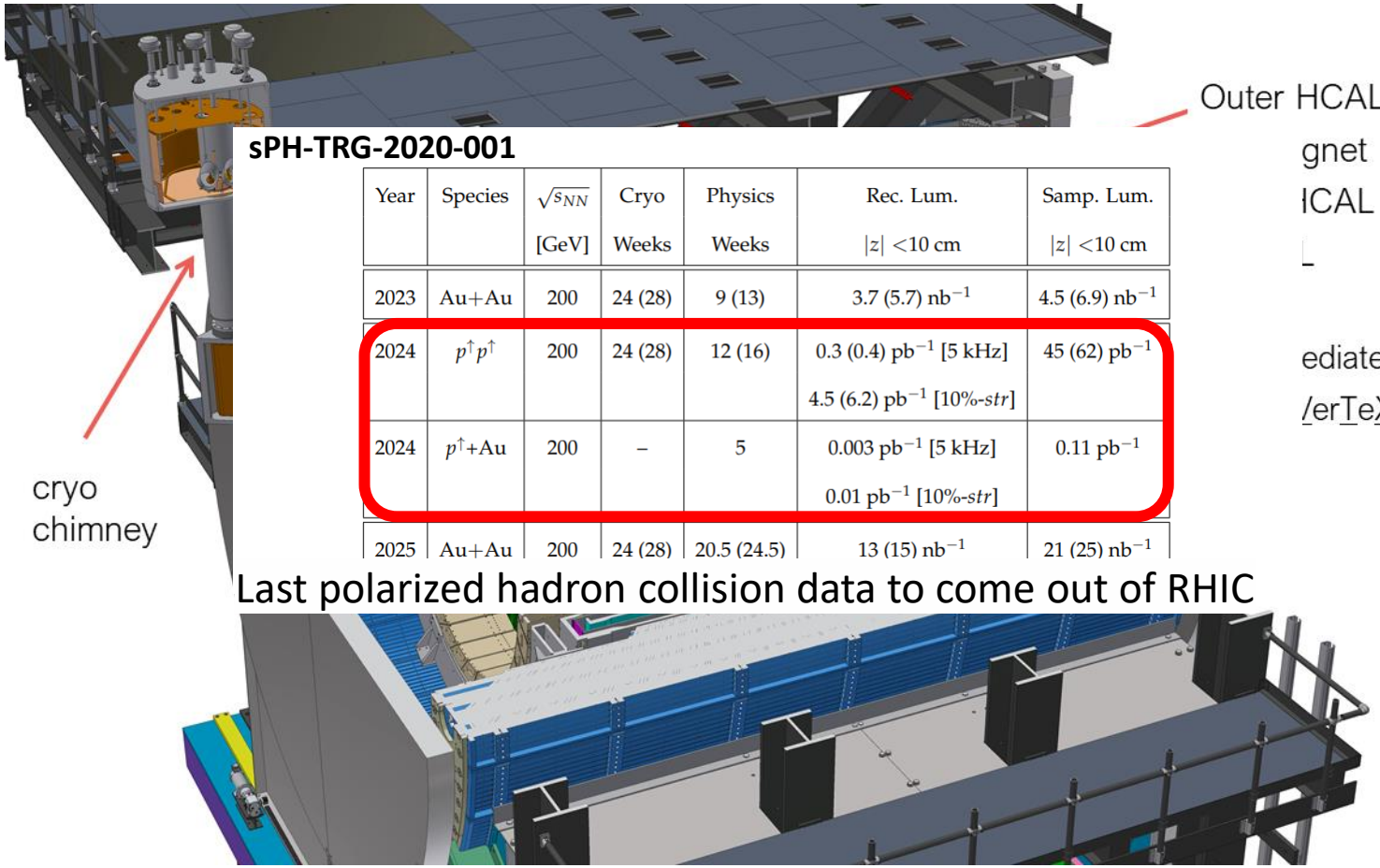

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Last polarized hadron collision data to come out of RHIC

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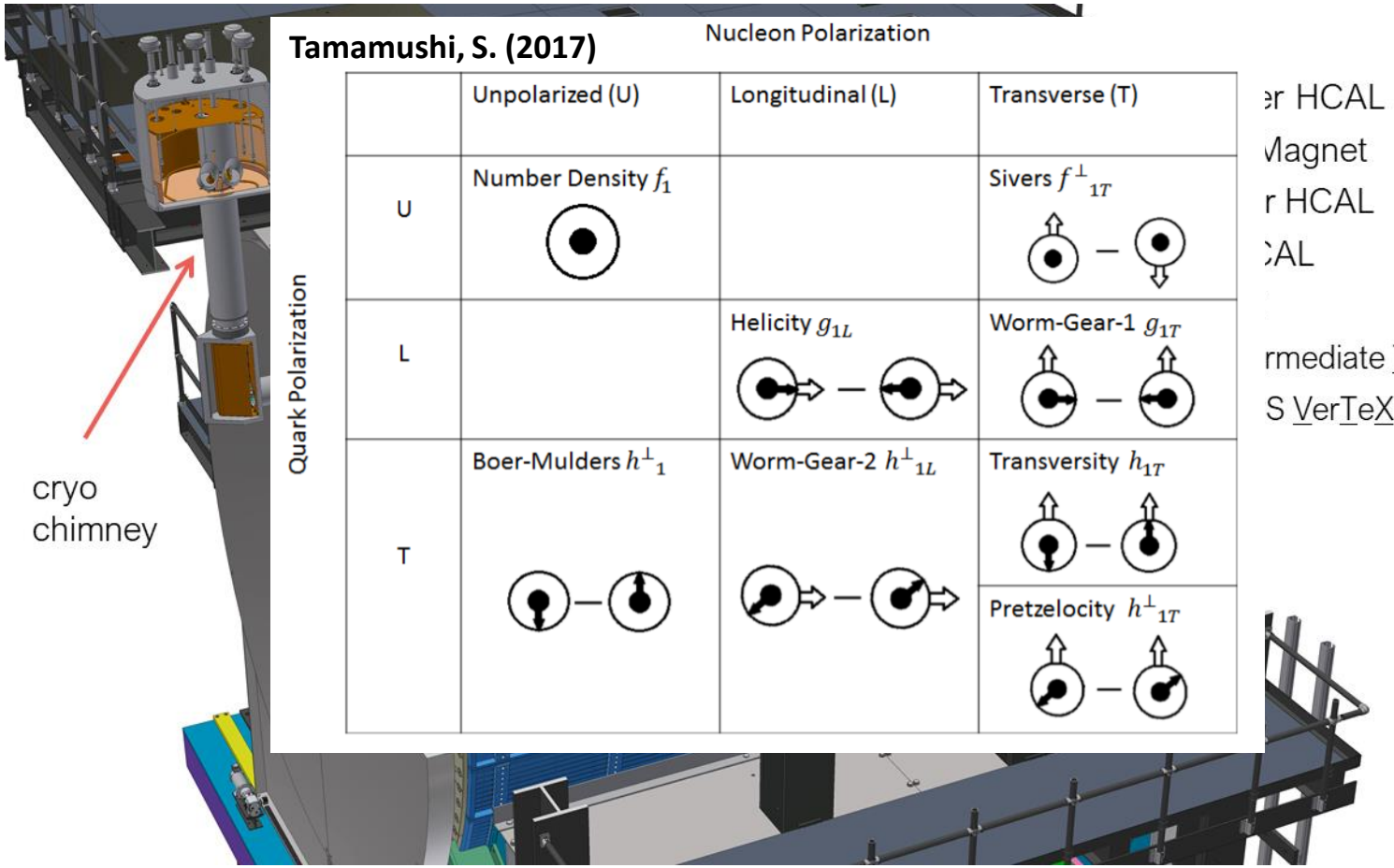

Tamamushi, S. (2017)

Nucleon Polarization

Quark Polarization	Unpolarized (U)	Longitudinal (L)	Transverse (T)
U	Number Density f_1		Sivers $f^{\perp}{}_{1T}$
L		Helicity g_{1L}	Worm-Gear-1 g_{1T}
T	Boer-Mulders $h^{\perp}{}_{1}$	Worm-Gear-2 $h^{\perp}{}_{1L}$	Transversity h_{1T}
			Pretzelocity $h^{\perp}{}_{1T}$

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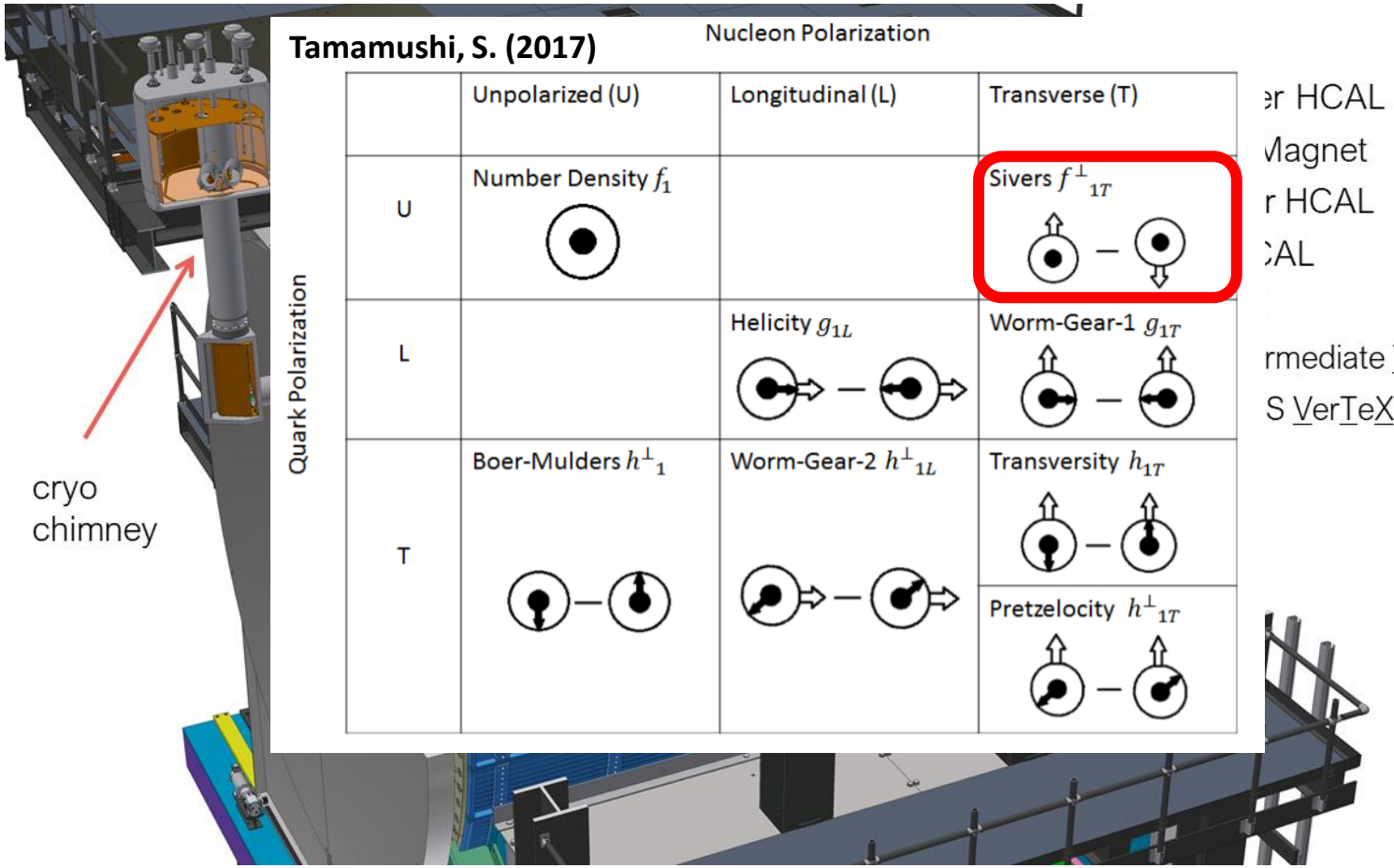

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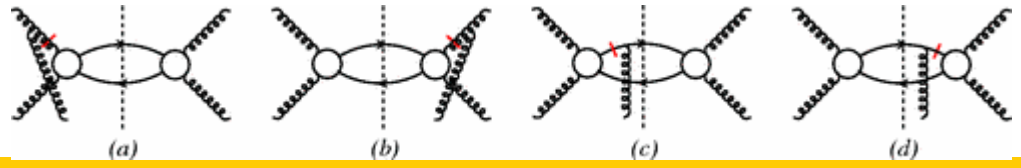
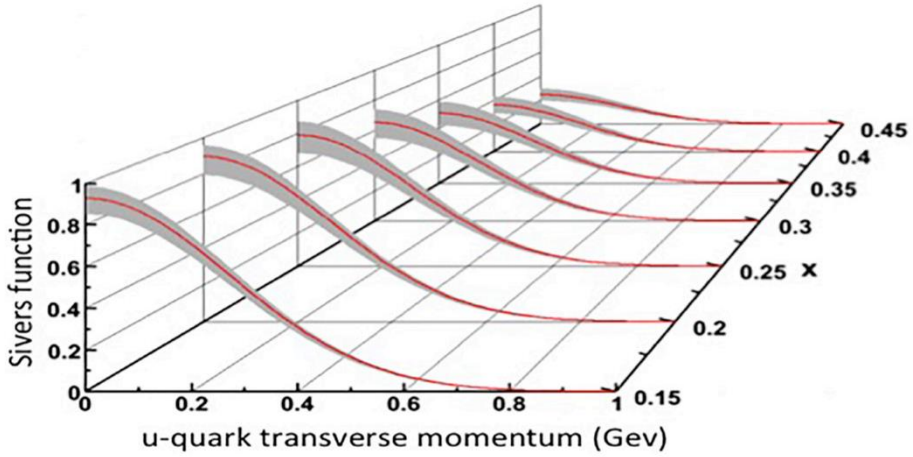
Transverse Spin Measurements in $p^{\uparrow}+p^{(\uparrow)}$ and $p^{\uparrow}+Au$

Sivers Transverse Momentum Dependent PDF

- $f_{1T}^{\perp}$ = distribution of parton transverse momentum in a transversely polarized proton
  - Can be measured in p+p(Au) systems via jet and photon channels
  - Choice of channel determines sensitivity to particular parton species
- Connected to twist-3 framework
  - Twist-2 → *traditional* PDF/FFs (one incident parton – one fragmenting parton)
  - Twist-3 → introduce gluon interaction with incident or fragmenting parton (one incident parton + g – one fragmenting parton | one incident parton – one fragmenting parton + g)
  - E.g. trigluon correlations





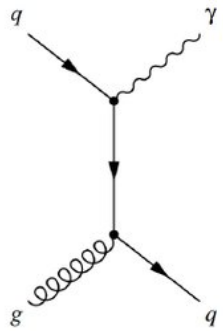
2015 Nuc. Science Long Range Plan

Phys. Rev. D 78, 114013

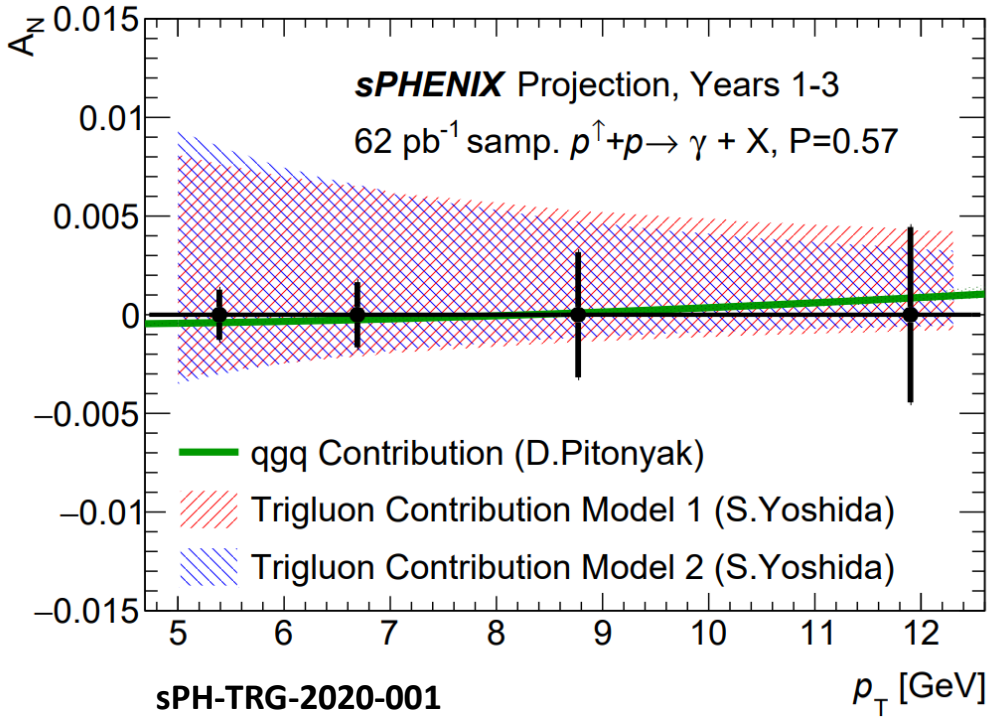
Gluon Dynamics via Transverse Single Spin Asymmetry A_N

Direct Photon Asymmetry

- Will be used to constrain twist-3 trigluon correlator in transversely polarized protons
  - Related to $f_{1T}^{\perp}$ of gluons in the proton
- Insensitive to hadronization effects at LO
- $A_N(\phi_q) = \frac{1}{P}\frac{Y^{\uparrow} - R \cdot Y^{\downarrow}}{Y^{\uparrow} + R \cdot Y^{\downarrow}} = \frac{1}{P}\frac{L(\sigma^{\uparrow}(\phi_q) - R \cdot \sigma^{\downarrow}(\phi_q))}{L(\sigma^{\uparrow}(\phi_q) + R \cdot \sigma^{\downarrow}(\phi_q))}$



Phys. Rev. C 92, 014907



sPH-TRG-2020-001

Gluon Dynamics via Transverse Single Spin Asymmetry A_N

Heavy Flavor Asymmetry

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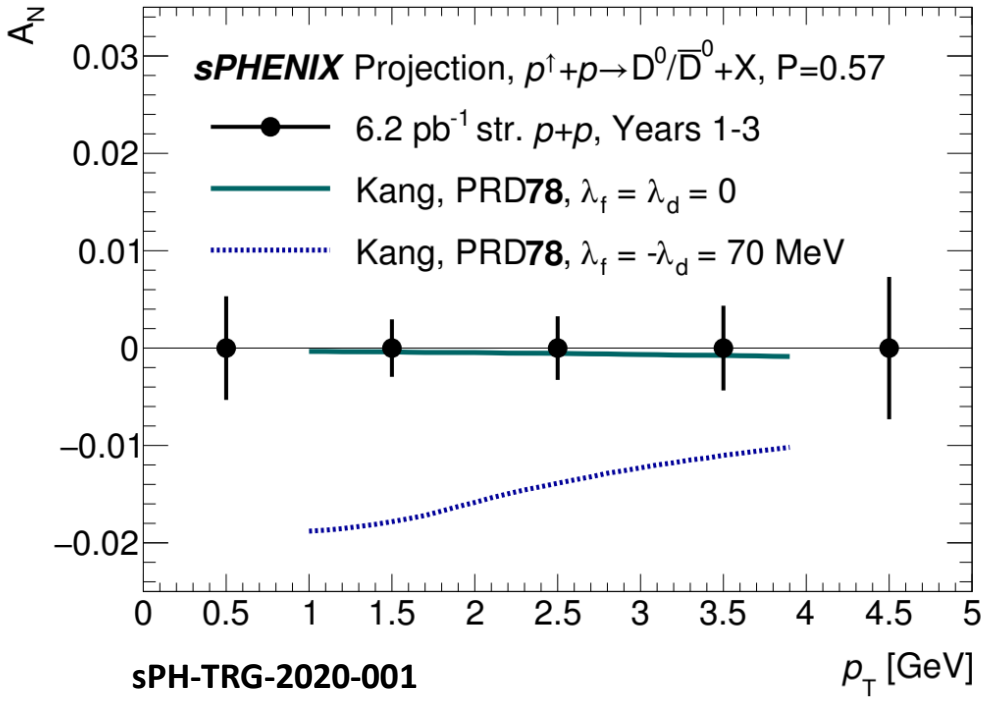
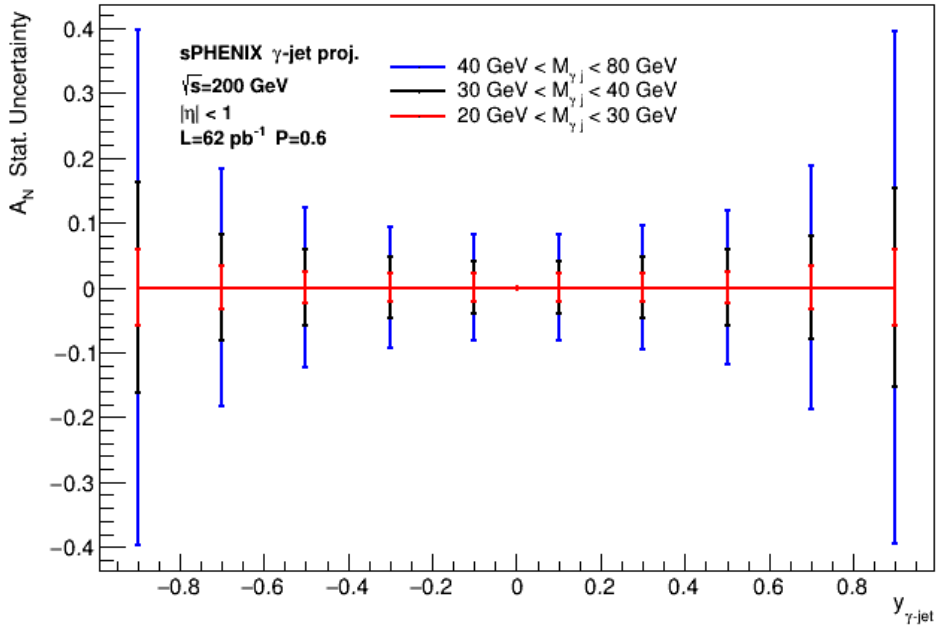
- Insensitive to hadronization effects at LO
- $A_N(\phi_q) = \frac{1}{P}\frac{Y^{\uparrow} - R \cdot Y^{\downarrow}}{Y^{\uparrow} + R \cdot Y^{\downarrow}} = \frac{1}{P}\frac{L(\sigma^{\uparrow}(\phi_q) - R \cdot \sigma^{\downarrow}(\phi_q))}{L(\sigma^{\uparrow}(\phi_q) + R \cdot \sigma^{\downarrow}(\phi_q))}$
- Possible due to sPHENIX streaming DAQ
  - 10% of collisions will be recorded in this triggerless configuration



Gluon Dynamics via Transverse Single Spin Asymmetry A_N

Gamma-jet Asymmetry

- Gluon-induced Compton scattering
  - Constrain gluon p_T distribution in polarized proton
  - sPHENIX is designed to be a jet detector due to the relevance of this and similar channels to heavy-ion physics



Parton Dynamics via A_N

Gamma-jet Asymmetry

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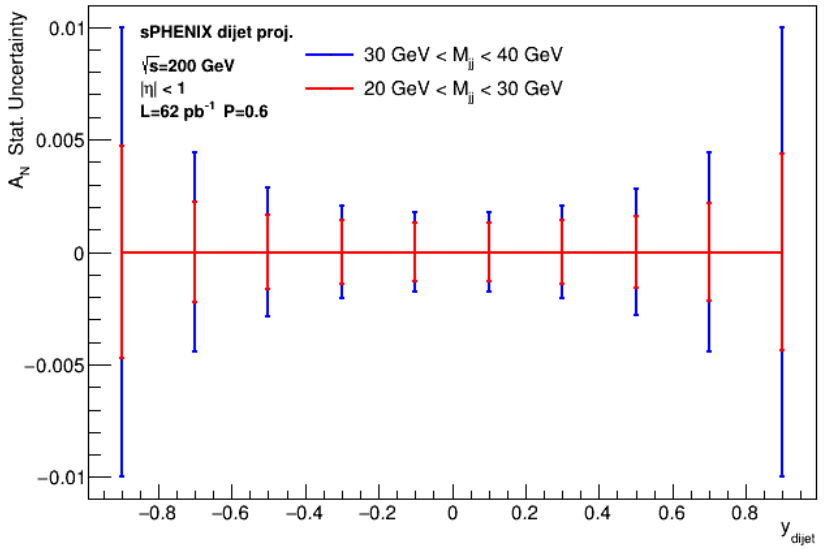
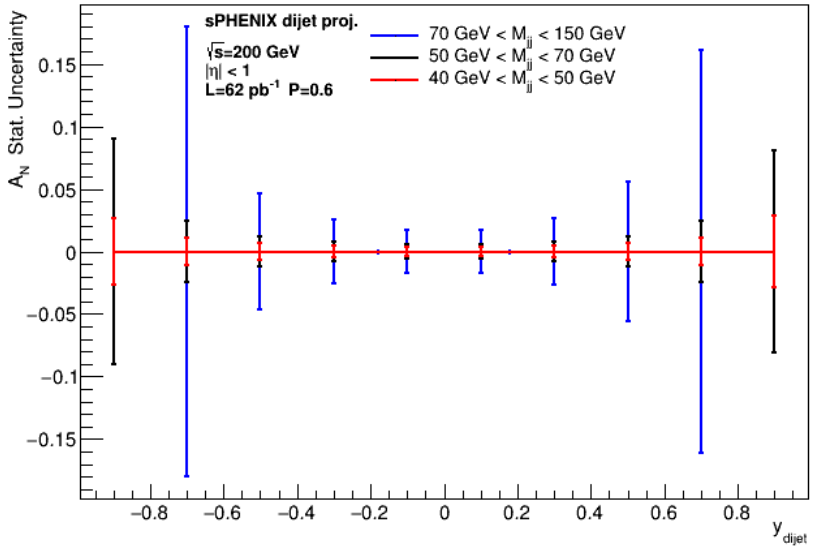
Dijet Asymmetry

- Sensitive to gluon and light quark Sivers TMD PDFs
- Charge-tagging for flavor-dependent Sivers asymmetry measurement





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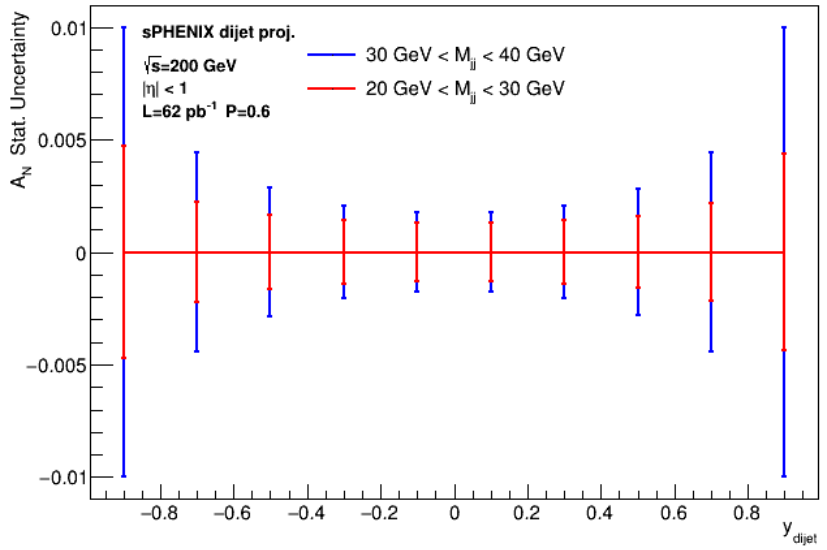

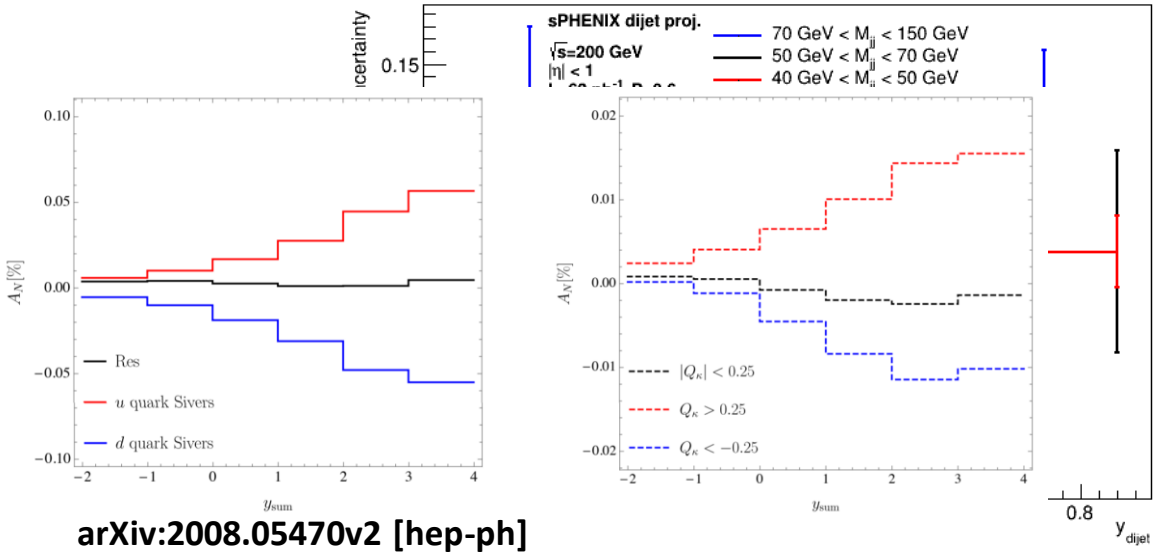

arXiv:2008.05470v2 [hep-ph]

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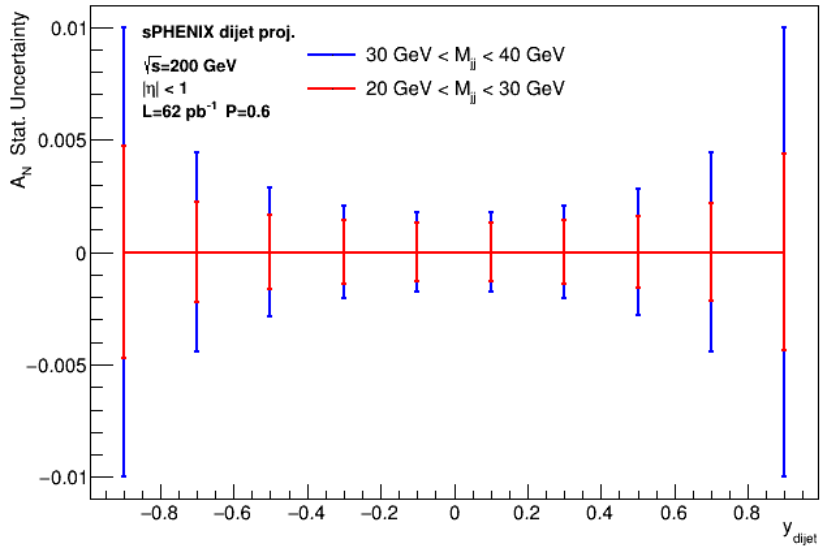
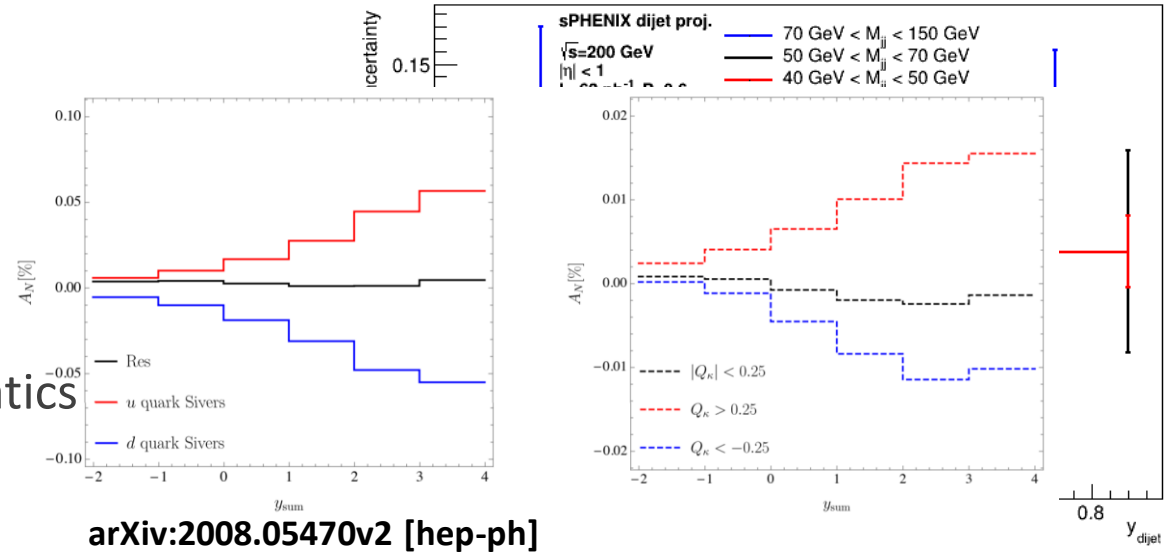
Both channels constrain LO parton kinematics





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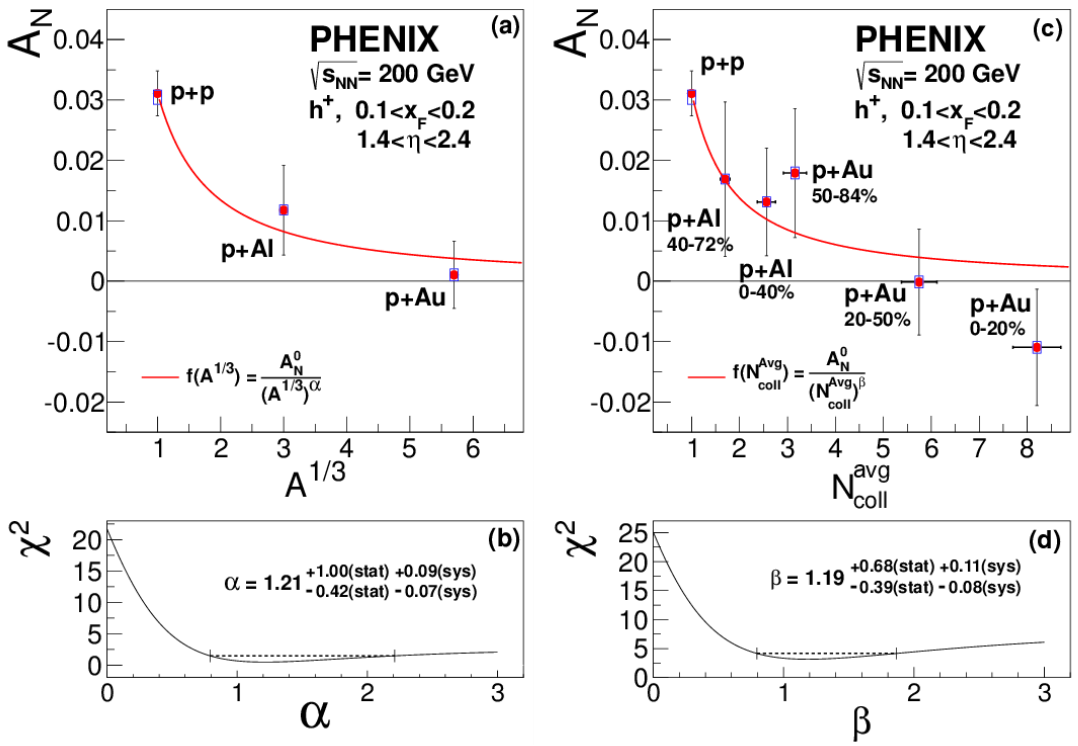
Nuclear Effects in A_N

Charged hadron Asymmetry

- Noticeable A_N suppression in pA collisions
  - At forward pseudorapidity and intermediate x_F
  - Currently no consensus on this behavior

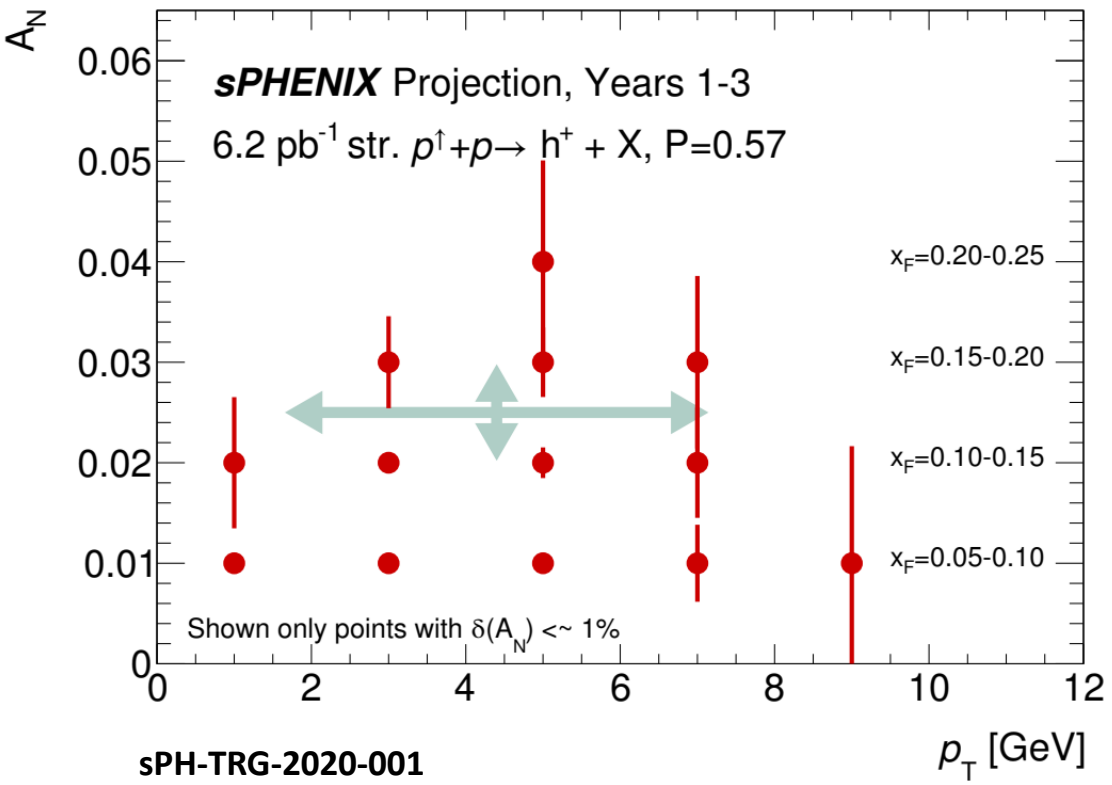


Phys. Rev. Lett. 123 (2019) 12, 122001

Nuclear Effects in A_N

Charged hadron Asymmetry

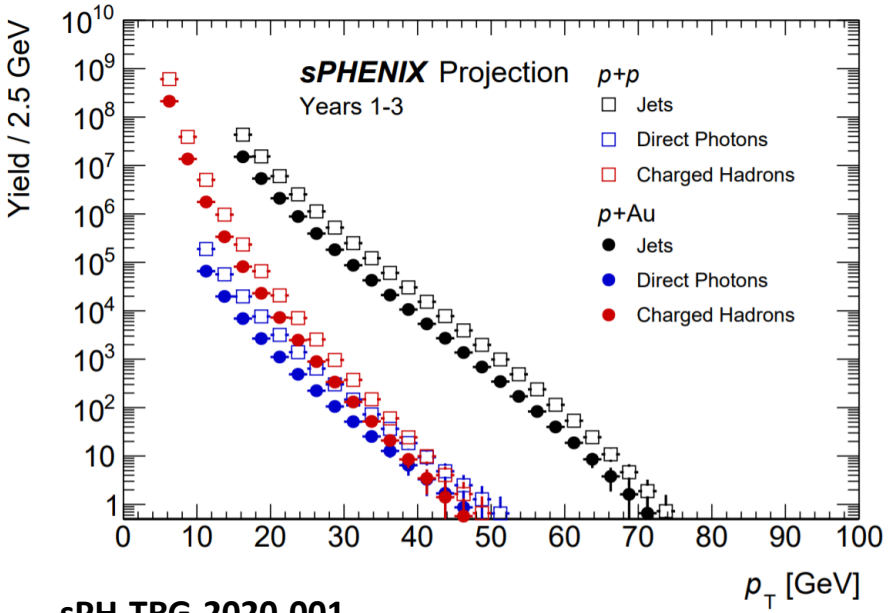
- Noticeable A_N suppression in pA collisions
  - At forward pseudorapidity and intermediate x_F
  - Currently no consensus on this behavior
- sPHENIX to improve statistics in this region of x_F
  - Specifically for $p^{\uparrow}+p^{\uparrow}$ and $p^{\uparrow}$+Au data points
  - Finer binning is expected



sPH-TRG-2020-001

Unpolarized Measurements in p+p and p+Au

Nuclear Effects in Hadronization



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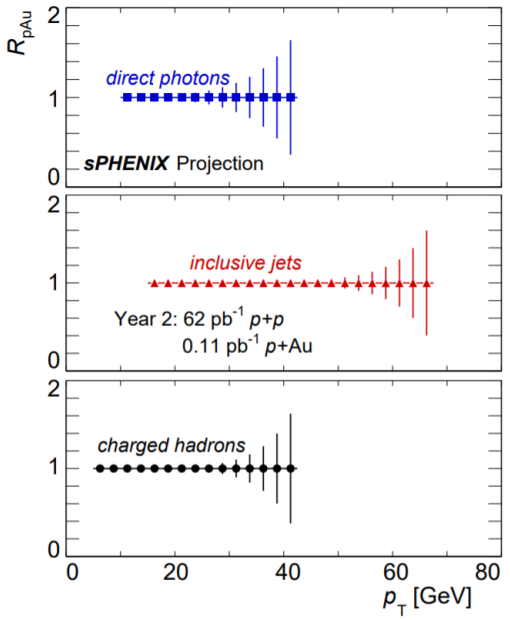
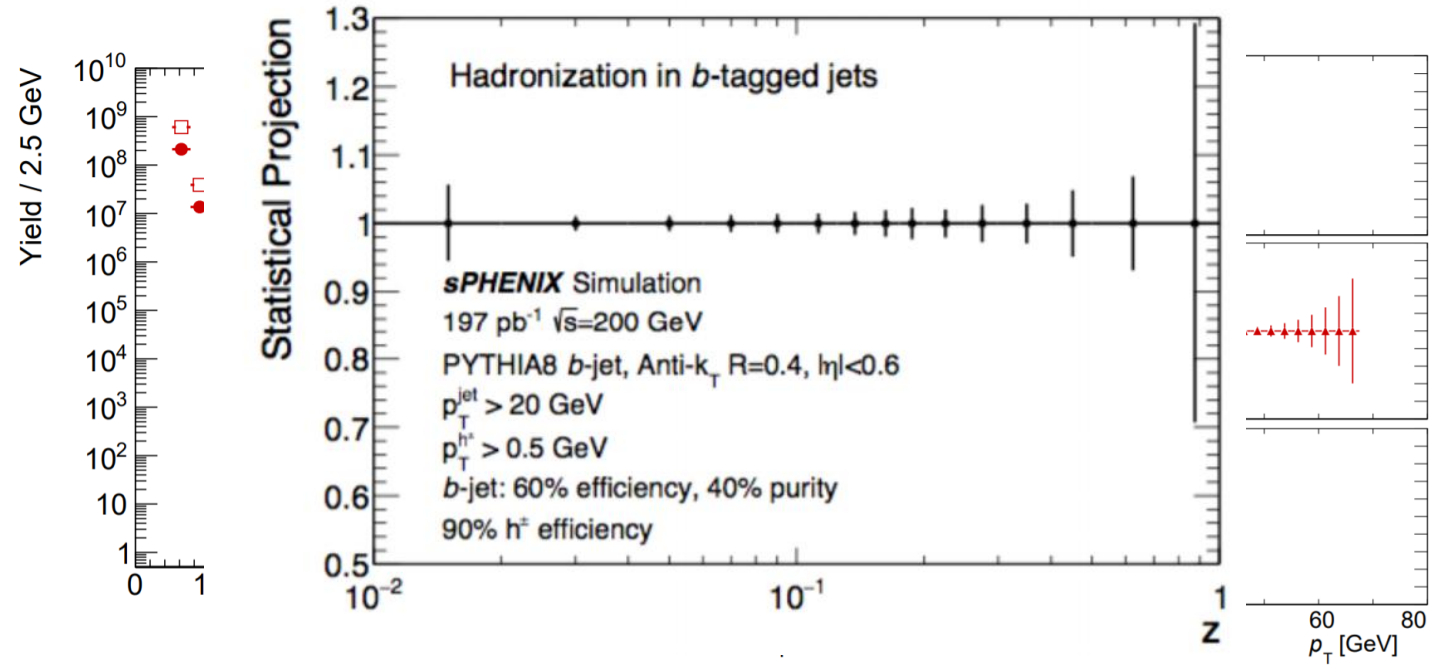


- Due to sPHENIX Central Barrel and Vertex Detector
  - Direct photons and charged hadrons up to ~45 GeV
  - Jets up to ~70 GeV
- Nuclear modification of hadron-in-jet distributions planned

Nuclear Effects in Hadronization



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  - w.r.t. z, j_T, r, etc.

$$z = \frac{p_j \cdot p_h}{|p_j|^2} \qquad j_T = \frac{|p_j \times p_h|}{|p_j|} \qquad \mathrm{r} = \sqrt{(\phi_h - \phi_j)^2 + (y_h - y_j)^2}$$

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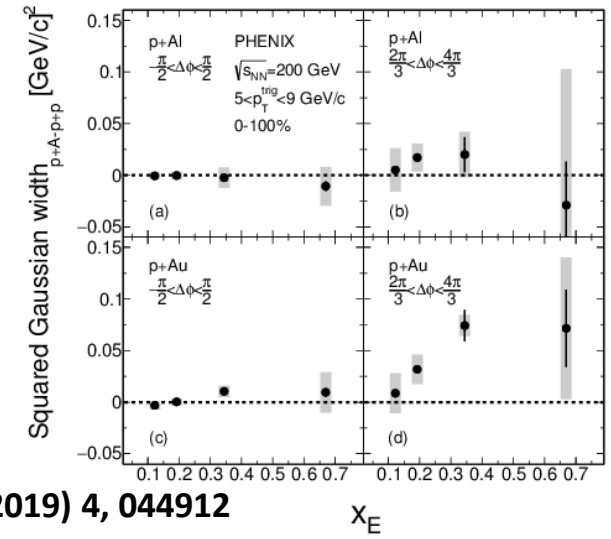
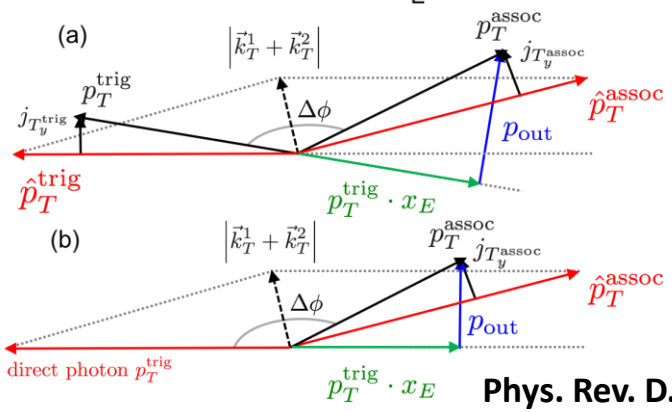


Phys.Rev.C 99 (2019) 4, 044912



Phys. Rev. D. 98 (2018) 7, 072004

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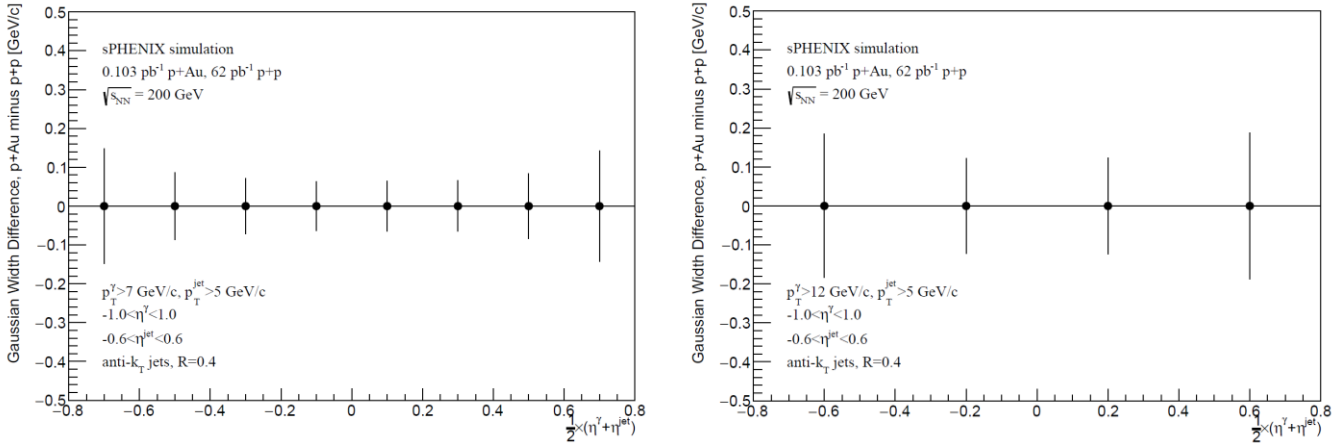
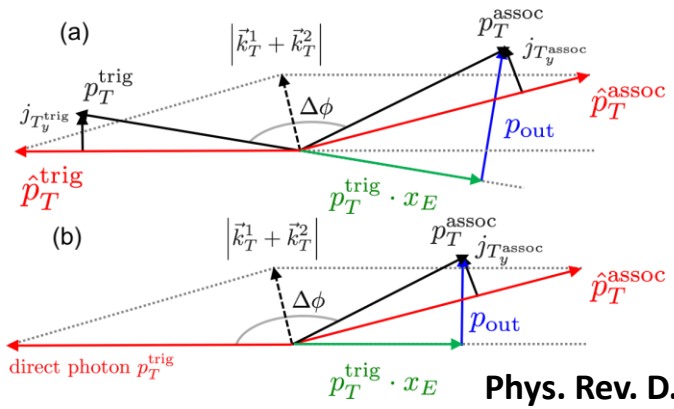
  - w.r.t. z, j_T, r, etc.
- Similarly, can measure transport coefficient for gamma-jet systems
  - $\langle\hat{q}L\rangle/2 \cong \langle p_{out}^2\rangle_{pA} - \langle p_{out}^2\rangle_{pp}$

Nuclear Effects in Hadronization





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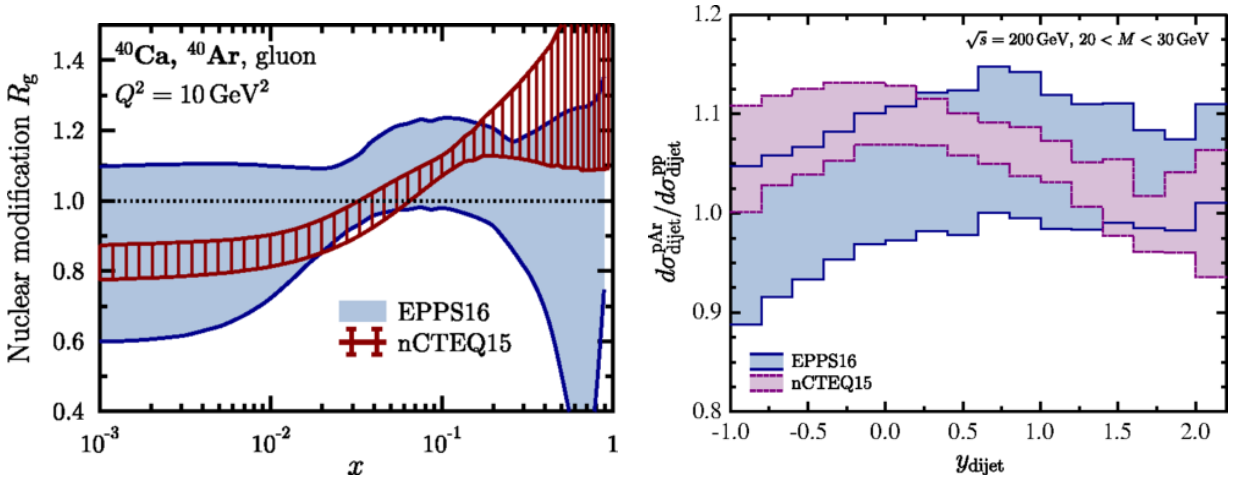
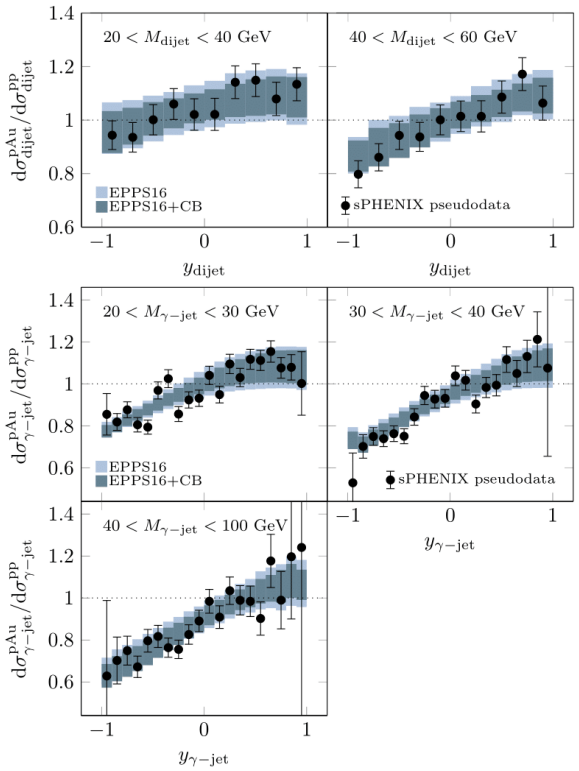
Constraining nPDFs

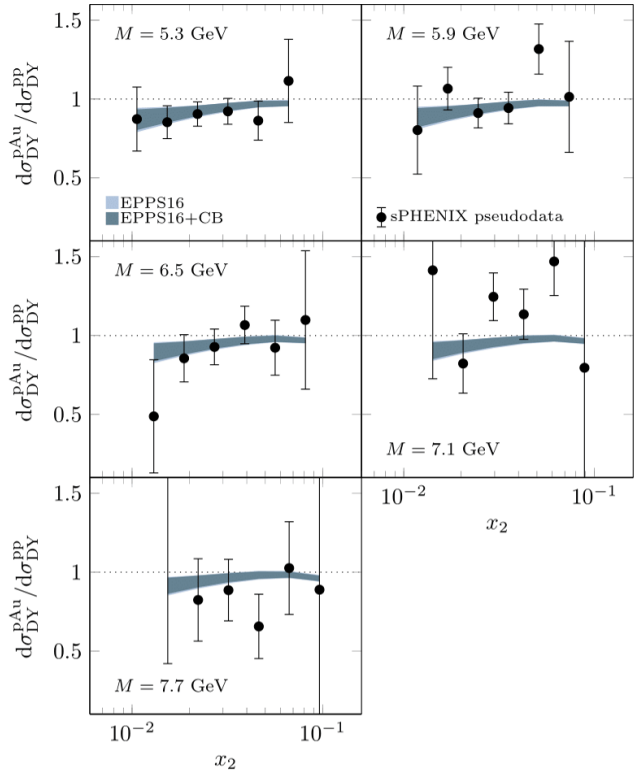


Phys. Rev. D 100, 014004

- nPDFs unconstrained at low Q^2

Constraining nPDFs





Phys. Rev. D 100, 014004

- nPDFs unconstrained at low Q^2
- Measurement of nuclear modifications can be used to constrain existing nPDFs
- Channels expected for simultaneous analysis
  - Drell-Yan
  - Dijet
  - Photon-jet

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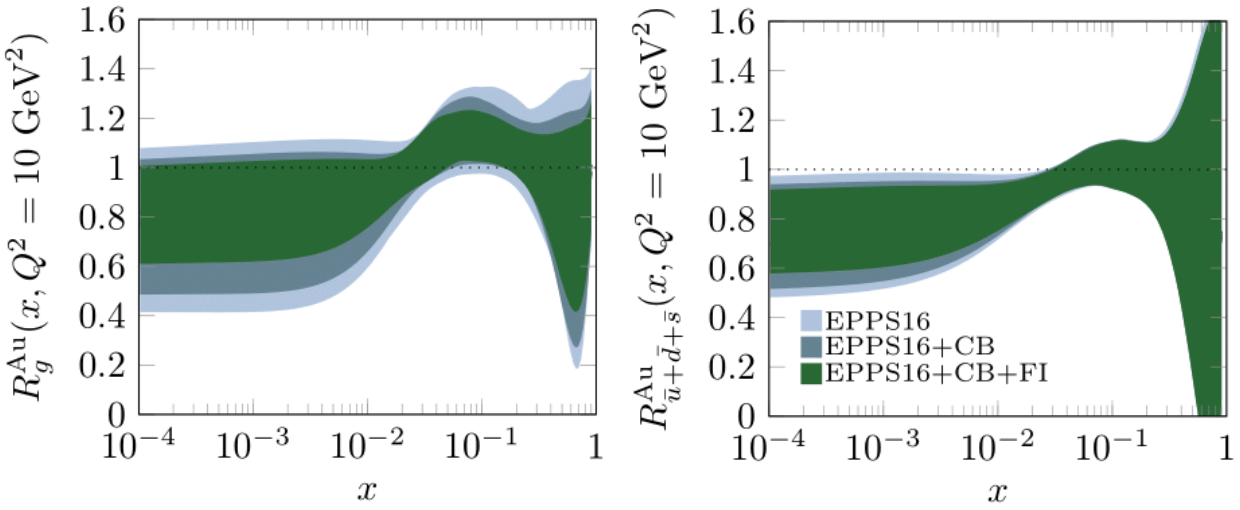


Phys. Rev. D 100, 014004

*Uncertainties from constraining EPPS16 nPDFs with sPHENIX Central Barrel ("CB") measurements

- nPDFs unconstrained at low Q^2
- Measurement of nuclear modifications can be used to constrain existing nPDFs
- Channels expected for simultaneous analysis
  - Drell-Yan
  - Dijet
  - Photon-jet
- Expecting improved uncertainties in gluon and antiquark nPDFs with this method
  - Particularly in shadowing region

Further Prospects

- Sivers via inclusive jet A_N
  - Uncertainty expected on the order of 10^{-4}
  - Complementary study to be done at EIC
- Collins Fragmentation Function
  - $H_1^{\perp}$ = distribution of in-jet hadron transverse momentum produced by a polarized quark
  - Provides us much needed access to transversity in protons
  - h_1 = parton transverse spin polarization in a transversely polarized proton
- Interference Fragmentation Function
  - Coupling between transversity and dihadron hadronization
  - Measured via dihadron angular distributions

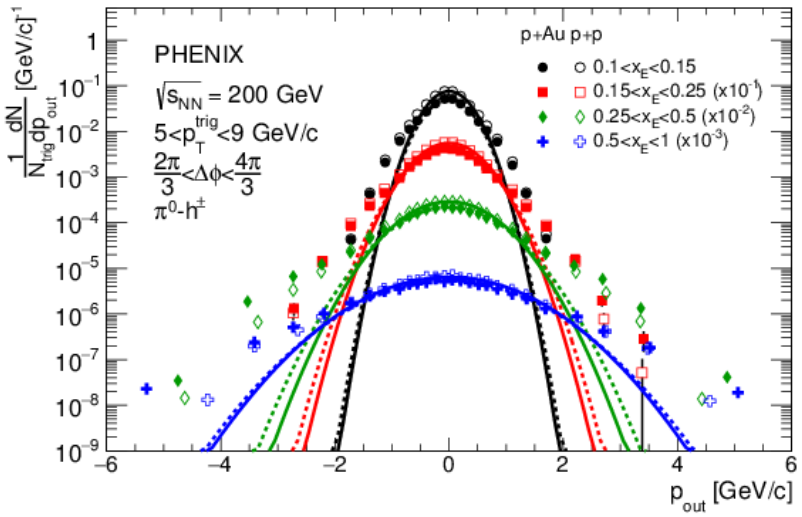
Summary

- sPHENIX is actively constructing a cold QCD program that will provide much needed constraints and measurements for parton dynamics and cold nuclear effects during our 2024 $p^{\uparrow}+p^{(\uparrow)}$ and $p^{\uparrow}$+Au runs
- Transverse spin dependent observables grant us access to
  - Gluon dynamics via photon, photon-jet (new), heavy flavor, and dijet asymmetries
  - Quark dynamics via charge-tagging in dijet channel
  - A_N nuclear and pseudorapidity dependencies via inclusive hadron measurements
- Spin-independent measurements at sPHENIX will contribute to understanding of transport coefficients as well as the nuclear modification of
  - Direct photons, charged hadrons, and inclusive jet production
  - Heavy flavor distributions in jets
  - Gluon and antiquark PDFs via Drell-Yan, dijet, and photon-jet channels in p+Au

Additional Collaborators Welcome!

Backup

p_{out} Distribution



Compton Scattering Dominance